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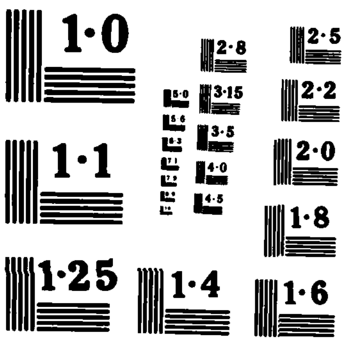

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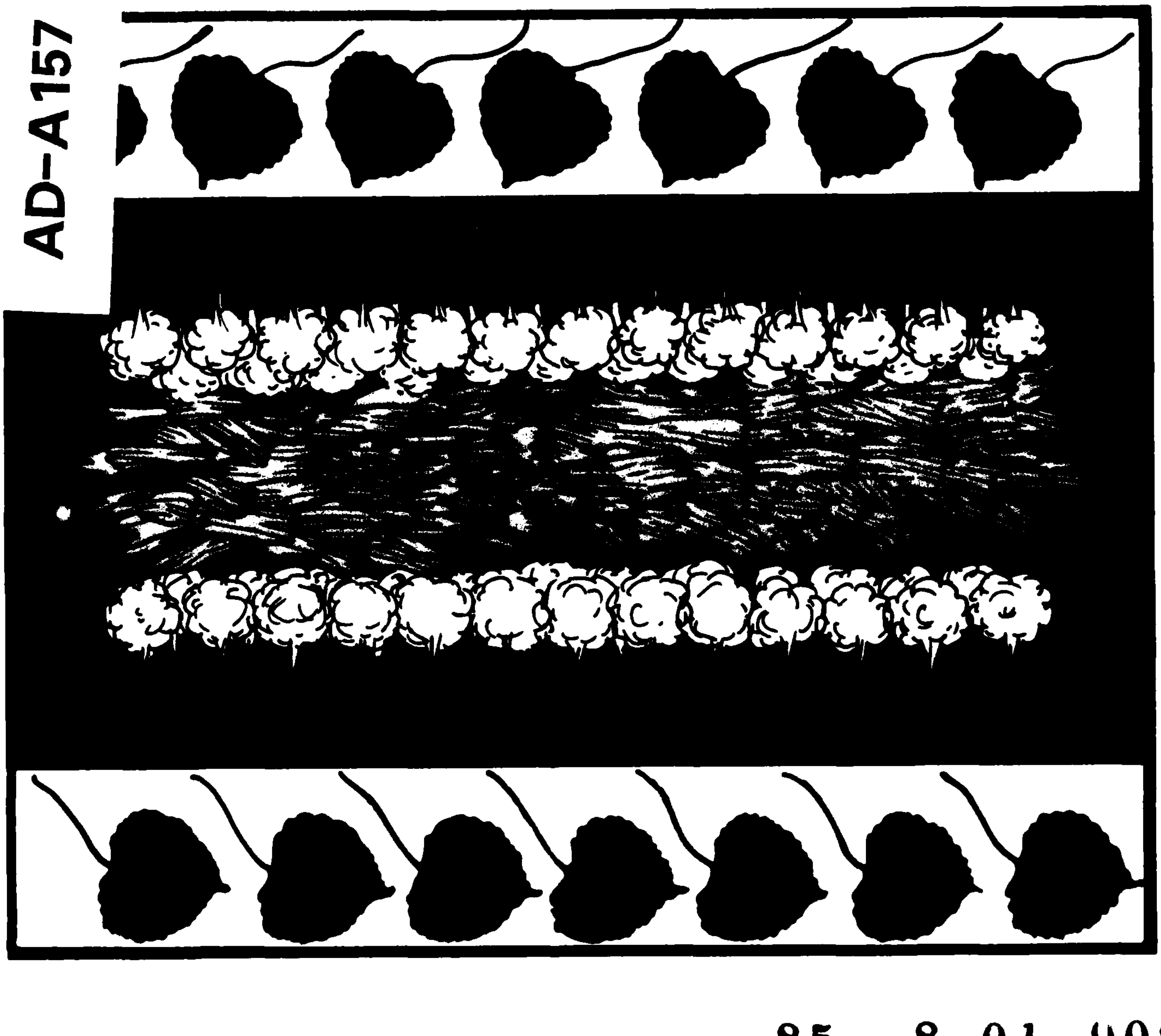
Steam-Injection Pressing of Isocyanate-Bonded Aspen Flakeboards

Latitudes and Limitations

Robert L. Geimer



Abstract

Injection of steam into a flakeboard mat during pressing significantly reduces press times. One-half-inch-thick 0.640 specific gravity (SG) isocyanate-bonded aspen flakeboard can be cured in 60 seconds by injecting 99 Btu's of steam energy per pound (Btu/lb) of board. Press time may be reduced to 40 seconds when energy consumption is increased to 177 Btu/lb of board. Two-inch-thick 0.640 SG board can be pressed in 201 seconds with 185 Btu/lb.

Blister formation in high-density thin boards and temperature variation in low-density thick boards were compensated for with press cycles individually suited for each combination of board thickness and SG.

Keywords: Steam, steam injection, heat, heat transfer, isocyanate, aspen, flakeboard, ring flake, disk flake, energy, press schedule, press time.

per letter on file

July 1985

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Steam-Injection Pressing of Isocyanate-Bonded Aspen Flakeboards
Latitudes and Limitations

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Introduction

Particleboard and flakeboard manufacturers operating in a competitive economy constantly strive to increase production rates without increasing costs or sacrificing quality. In the past 30 years we have seen substantial improvements in the manufacturing process; however, motivation for improved production remains. In modern plants, the production bottleneck is the hot press. Specifically, the press cycle is limited by the time it takes to heat the center of a board to a temperature that activates the thermosetting resin. This time increases in a nonlinear fashion with board thickness. The 45- to 90-second warmup period characteristic of a 1/2-inch-thick board may be as long as 45 minutes for a 2-inch-thick board. Substantial reductions in thickboard press times would create new, economically viable markets for what is now considered a low profit item.

A process developed at the Forest Products Laboratory shortens press times by injecting saturated steam directly into the mat (Geimer 1983) (fig. 1). The process reduces press times for 1/2-inch-thick flakeboard by 60 percent, from 4 minutes to 1-1/2 minutes, without degrading internal bond (IB) or flexure properties (Geimer 1982). Press-time reductions of 90 percent are possible when using this steam-injection pressing system with thicker boards.

In past work, we developed the principles of steam-injection pressing using Douglas-fir ring flakes and phenolic resin. Research was mainly restricted to the fabrication of 1/2-inch-thick boards having a specific gravity (SG) of 0.640. The work described here was conducted using an aspen furnish and an isocyanate binder and extended the application of steam-injection pressing to other board thicknesses and SG's. Of particular interest was the manipulation of pressing variables (i.e. steam flow, steam time, closing rate, etc.) to enhance the relationship between energy consumption and total press times.

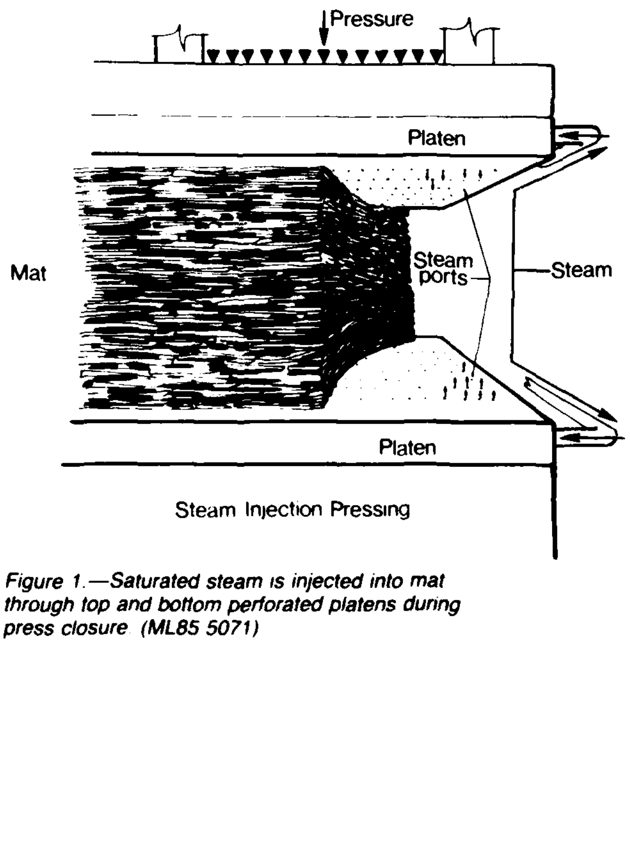

Figure 1.—Saturated steam is injected into mat through top and bottom perforated platens during press closure. (ML85 5071)

Experimental Procedures

Board Fabrication

Flakeboards were constructed to three thicknesses and two levels of SG.

Thickness	SG
1/2 inch	0.640-0.801
1-1/4 inches	0.560-0.721
2 inches	0.480-0.640

The assignment of SG levels was based on current product trends wherein SG decreases with increasing board thickness. For each board thickness and SG level, a series of from five to nine individual flakeboards were made at varying press and steam times. No particular set of conditions were replicated for the purpose of establishing statistically significant board properties.

The furnish consisted of a 50:50 mixture of 0.020-inch-thick by 2-inch-long by random-width aspen ring flakes and 0.020-inch-thick by 2-1/2-inch-long by random-width aspen disk flakes. With the exception of a few 1/2-inch-thick 0.801 SG boards made with 7 percent isocyanate, all boards were constructed using 3 percent isocyanate resin based on ovendry (OD) wood. Moisture content of the mat prior to pressing was below 4 percent (OD wood basis).

The board dimensions of 25 by 29 inches provided a 1-1/2-inch margin beyond the periphery of the steam platen perforations to act as a steam seal. The steam-injection platens, perforated with 3/32-inch-diameter holes on a 1/2- by 2-inch spacing, were attached to the regular oil-heated platens which in turn were maintained with few exceptions at a temperature of 375 °F. The steam-injection system is detailed in a previous report (Geimer 1982).

Press Control and Data Collection

The press was programmed through a computer, which in conjunction with the press' electronic system, provided excellent control of platen position and board pressure (Geimer et al. 1982). The computer also performed auxiliary functions of steam valve actuation and data collection. Variables measured included board temperature, hydraulic pressure, press platen position, steam flow, and steam platen manifold pressure and temperature. Board temperature was initially measured only at the mid-thickness of the board's center location. Measurements were later expanded to include edge and corner positions. During the critical portion of the press cycle beginning some 5-10 seconds prior to steam injection and lasting for a total of 45-60 seconds, information was recorded every 0.5 second. Thereafter, the recording time was lengthened to between 1 to 5 seconds. Within 5 minutes after press opening, data were available in the form of both a hard copy readout and graphs of selected variables versus time. Press schedules were altered after each pressing to provide what was believed would be the most useful information in regard to press times, steam-injection schedule, total energy consumption, and visual board quality.

Testing

Cutting diagrams for test specimens are shown in figures 2 and 3. The samples were tested for internal bond (IB) and bending modulus of elasticity (MOE) and modulus of rupture (MOR) according to procedures outlined in ASTM D 1037-72A (American Society for Testing and Materials 1976). Linear expansion (LE), thickness swelling (TS), and water adsorption (WA) were measured after each successive exposure to ovendry (OD), 65 percent relative humidity, vacuum pressure soak (VPS), and a second ovendrying condition. In addition, density gradients were determined with a gamma ray density measuring device[1] (Laufenberg 1984). Corner or edge delaminations prevented complete testing of some boards.

[1] Laufenberg, T. L. Using gamma radiation to measure density gradients in reconstituted wood products. Manuscript in preparation. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI; 1985.

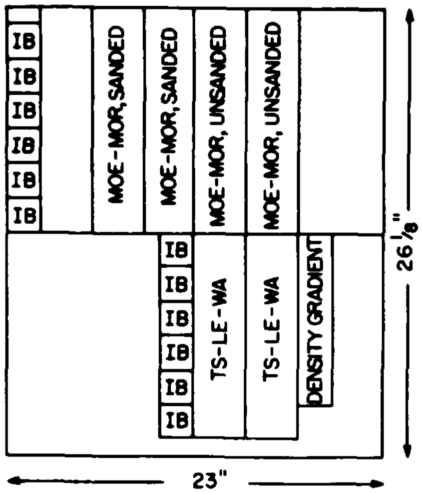

Figure 2.—Cutup diagram for 1 2-inch-thick boards. Sample size: Internal bond (IB) 2 by 2 inches; modulus of elasticity (MOE) and modulus of rupture (MOR) 3 by 13 inches; thickness swell (TS), linear expansion (LE), water absorption (WA) 3 by 12 inches; and density gradient 2 by 10 inches. (ML85 5073)

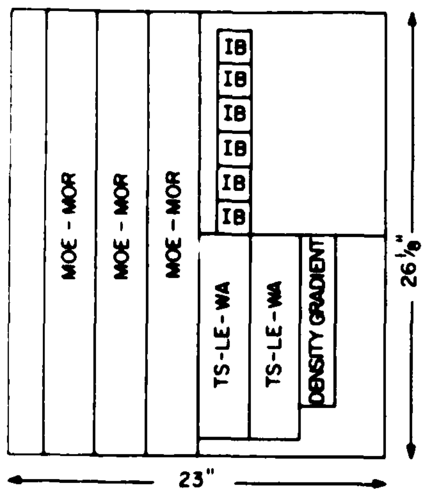

Figure 3.—Cutup diagram for 1-1 4- and 2-inch-thick boards. Sample size: same as figure 3 except modulus of elasticity (MOE) and modulus of rupture (MOR) 3 by 26 inches. (ML83 5072)

Discussion

I chose aspen for this study because of its present widespread use in structural flakeboards. Boards from this low-density species generally are manufactured to a relatively high compaction ratio (ratio of board density to species density) and are prone to moisture release problems in the form of blows or blisters. The extent of this problem is of major interest in the investigation of steam-injection pressing, where additional moisture is added during the press cycle. Disk flakes were mixed with the ring-flake furnish to intensify the problem of moisture release. Although relatively new to the particleboard industry, isocyanate resin was chosen for this study because exploratory work showed the resin's characteristic of fast cure at low temperatures to be well suited to steam-injection pressing.

Pressing variables and board properties are shown in tables 1-6. The board number indicates the month, day, and sequence of board manufacture. To make comparisons easier, the board variations are arranged in descending order of (1) press time and (2) energy consumption rather than chronologically. Press schedules shown here do not necessarily represent minimum or optimized conditions but rather were chosen to ascertain the latitudes and limitations of the steam-injection system. Total press times were kept relatively short to emphasize the effect of the other variables.

During the course of the experiment, it became apparent that a set of press conditions that worked well with one combination of board thickness and SG was not necessarily correct for another board type. Although considerable changes were made in press schedules, they were all intended to meet the basic criteria of steam-injection pressing, i.e., introduction of steam prior to the mat reaching a SG of between 0.416 and 0.448 and development of 212 °F temperature in the mat's centerline prior to the partially compressed mat reaching a SG of 0.577 (Geimer 1983). Failure to obtain these conditions in a few cases proved disastrous to bond formation.

With the exception of steam flow rates and steam energy consumption, all pressing data shown were taken from actual computer-monitored information. Steam flow rates are target values based on valve settings and flow measurements made with an open press. Resistance to steam flow because of mat compaction actually causes a gradual reduction of steam flow during the press cycle. Steam energy consumed by boards made in the early stages of the experiment was calculated using target steam flow rates and the programmed time schedule. Energy values for boards numbered higher than 5/4 were calculated using computer-measured flow rates. Energy values are expressed as Btu's per pound (Btu/lb) of OD board and are referred to in the text as Btu's.

Values in the column entitled "entry specific gravity" give the actual SG of the mat at the time steam was first introduced. In most cases, steam introduction was programmed to start at a specific mat density, determined by the computer monitored press position. Another method, which indirectly reflects mat density and proved to be repetitive, initiated steam flow when a selected hydraulic pressure was reached.

Results

Equipment modifications made during the course of the experiment enabled steam flow to be changed between two rates. This ability to change flow rates permitted a finer degree of optimization of press time and energy consumption. With thick boards, high flow rates are often needed to achieve fast temperature rise in the board. In some cases, once the maximum temperature has been reached in all sections of the board, temperature can be maintained with reduced steam flow. Conversely, with thinner boards it sometimes is advantageous from an energy standpoint to introduce steam at low flow rates and increase flow when the mat SG becomes higher. In this way, higher temperatures can be reached.

Press closing rates are given in distance rate change (in./s) and average SG rate change (ΔSG/s). These figures are taken from the monitored data and reflect any deviation from the programmed events caused by either controller characteristics or dynamics of the system. Note that press closure rates as measured by changing distance do not follow the same pattern as those calculated from changing SG. The difference reflects the nonlinear relationship between mat SG and mat thickness (fig. 4). The rate of change in SG may be more meaningful than distance rate change in explaining the effects of press closing rates on board characteristics. Consideration should be given to this method of monitoring and controlling closure in the development of modern press schedules.

Total press time as referred to herein is the elapsed time between initial introduction of steam and final press opening. In most cases, total press time included a 10-second decompress period. When pressing 1/2-inch-thick 0.640 SG board, approximately 10 seconds were needed to close from a position where both platens touched the mat to the point of steam injection. This period increased to approximately 20 seconds for a 2-inch-thick board.

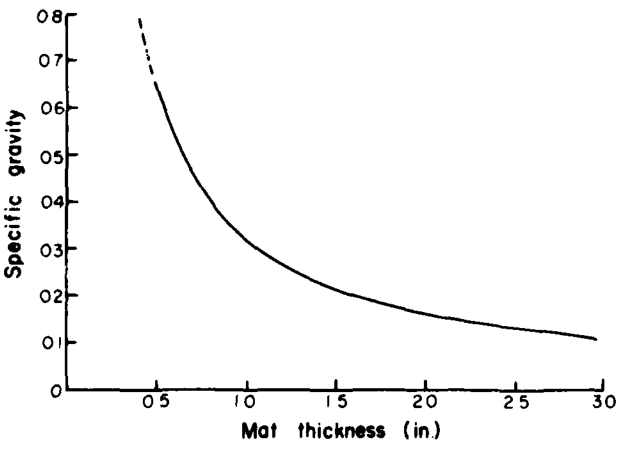

Figure 4.—Specific gravity (SG) is a nonlinear function of mat thickness. $SG = K/t$ where t = thickness and K = weight/area. Relation is shown for a 1/2-in-thick 0.640 SG board. K = 0.032. (ML85 5074)

For those unaccustomed to steam-injection pressing techniques, the difference of a few seconds may seem trivial. The response of variables to changes in the press cycle, however, is often rapid and decisive. Data given herein, although not showing all the changes occurring within the boards, will provide an understanding of the parameters of steam-injection pressing. Close scrutiny of tables 1-6 will indicate the sensitivity of the system.

1/2-Inch-Thick 0.640 SG Boards (Table 1)

No problems were encountered in manufacturing the 1/2-inch-thick 0.640 SG boards except when press time was reduced to 22 seconds or less. A press schedule that worked well with this group of boards called for an *early* (0.260 SG) introduction of steam at a medium flow rate (540 lb/h). *Later*, when the mat had been compressed considerably (0.500 SG) and higher temperatures could be reached, the steam flow was increased (board 5/24a). In several cases, even more energy was saved by interrupting the steam flow for a few seconds until the mat was compressed (5/25 and 5/24d). This interruption of steam flow works well with boards having a pressed SG less than 0.640. Problems with steam reentry are likely to be encountered in boards whose final SG is above 0.640.

Temperature in the 1/2-inch-thick 0.640 SG boards was monitored in all three positions: center, edge, and corner. In most cases there is little difference between maximum temperatures reached at the different locations. The temperatures are well above the activation point, approximately 220 °F, for the rapid curing of an isocyanate resin. Data given under the table heading "temperature delay" show the delay in seconds from the time steam was introduced to the point where the temperature in the center of the board at midthickness begins to rise. This time is approximately 1 second for 1/2-inch-thick board but may be as long as 8 seconds in a 2-inch-thick board. As a result of the fast temperature transfer, all 1/2-inch-thick boards had a uniform density profile across their thickness. Maximum temperatures are reached during the period of steam flow or shortly thereafter and decline rapidly to a level between 225 and 250 °F when the steam is shut off. Temperatures stabilize at this level for the remainder of the press cycle.

A blister formed on the surface of the board (5/24b) made in 22 seconds using steam energy of 158 Btu/lb of OD board (Btu's). Board 5/24e, made in 22 seconds using 101 Btu's, did not blister but had more out-of-press springback and showed a decline in board properties. The board (5/25a) made in 13.5 seconds had a slight delamination along one edge, which proved to be characteristic of short press cycles or poor temperature distribution and indicated insufficient resin cure. Data show that 1/2-inch-thick 0.640 SG boards can be made in 60 seconds using 99 Btu's, or in 40 seconds using 177 Btu's steam energy. Bending properties of the sanded and unsanded specimens were statistically identical. Modulus of elasticity and MOR values given in tables 1-6 are an average of all bending specimens.

1/2-Inch-Thick 0.801 SG Boards (Table 2)

Moisture release was the main problem encountered when making these higher density boards. At a SG of 0.80 (compaction ratio of 2.1:1) blisters were prone to form on the surface of the boards. Blisters result because of excessive steam pressure disrupting the bond, a localized high moisture spot preventing resin cure, or a combination of both. Reduction of backup platen temperature did not help. In an attempt to reduce the total steaming time, steam injection of board 5/25d was delayed until a mat SG of 0.395 was reached. Because of poor steam penetration and consequently low temperatures, this board contained delaminations in addition to some blisters.

Major changes were necessary to prevent blisters. We (1) increased resin content from 3 to 7 percent, (2) modified the press schedule to introduce steam at a lower mat pressure and reduce final closing pressures, and (3) increased press times and steam energy consumptions.

A board, free of blisters and having good physical properties, was made in 172 seconds using 373 Btu's. Successive trials showed that press times and energy levels could be reduced. The minimum time used to press a blister-free board was 152 seconds. One board (5/26e) was made with an even shorter press time but an excess of steam. Blisters developed, indicating that a longer time at maximum temperature could not compensate for reduced press time and excessive moisture. Therefore, when pressing high-density boards, a balance between maximum temperature duration and total press time must be maintained. No attempt was made to produce boards at the new press cycles with reduced resin content.

1-1/4-Inch-Thick 0.56 SG Boards (Table 3)

Edge and corner delaminations in the 1-1/4-inch-thick 0.56 SG boards were common. The problem proved to be related to poor temperature distribution which may be attributed to a progressive pressure differential occurring from the center of the board to its edges. The pressure drop is greater in thick, low-density boards where steam can escape easily.

With the exception of board 5/23, temperature was monitored only at the center position. Thermocouples placed in board 5/23 showed a large temperature difference between center, edge, and corner positions. Maximum temperature decreased from 318 °F in the center to 245 °F at the corners. Although this temperature differential is quite large, a delamination-free board was pressed in 140 seconds using 155 Btu's steam energy. It is assumed that the temperature differential was even greater in those boards where delamination occurred. Because of the design of the platen steam passages, the temperature differential was not symmetric, and delaminations occurred predominantly along the same edge of each board. In those cases where delamination was not severe, board properties were tested. Internal bond data showed that the resin cure was adequate in those portions of the boards receiving ample heat.

Most of the good boards, i.e., those containing no delaminations, were made using a high flow rate of steam (720 lb/h), which continued for some time following closure to final thickness. This permitted the temperature to rise to curing levels in the board extremities. The effect of steam flow rate can be seen by comparing results for board 4/14d, steamed at 260 lb/h for 12 seconds, to board 5/23, steamed at 720 lb/h for the same period. The low energy input of 55 Btu's obtained with the lower flow rate was insufficient to make a good board. Even when total energy input was approximately equal, higher flow rates produced better results (boards 4/15 and 4/18b). The minimum press time attempted with the 1-1/4-inch-thick 0.56 SG boards was 60 seconds. A board having no delaminations was made in this time using 370 Btu's steam energy.

As mentioned previously, press conditions were deliberately chosen to emphasize the effect of variables. This often resulted in a very fine line between success and failure in board production. Such was the case for boards 4/13 and 4/13a. The press cycle resulting in a board with good properties (4/13) was slightly altered for board 4/13a. A 4-second decrease in closing time and an 8-second reduction of steam precluded resin cure and caused the complete delamination of board 4/13a.

The press schedule including monitored rates of closure are shown for both boards in table 3. Steam flow was adjusted to 540 lb/h. Pressure, temperature, and position variables are plotted against time in figures 5 and 6. For the purpose of this description, zero time is designated as the moment when manifold pressure and temperatures suddenly rise indicating the entry of steam. At this point the SG of both boards was recorded as 0.358. The difference between this value and the programmed entry of 0.352 implies an error of 0.033 inch or 0.13 second, well within the accuracy limits of the control equipment and recording devices. At zero time, the pressure on board 4/13 was 265 pounds per square inch (lb/in.^{2}) and the pressure on 4/13a was slightly higher, 285 lb/in.^{2}.

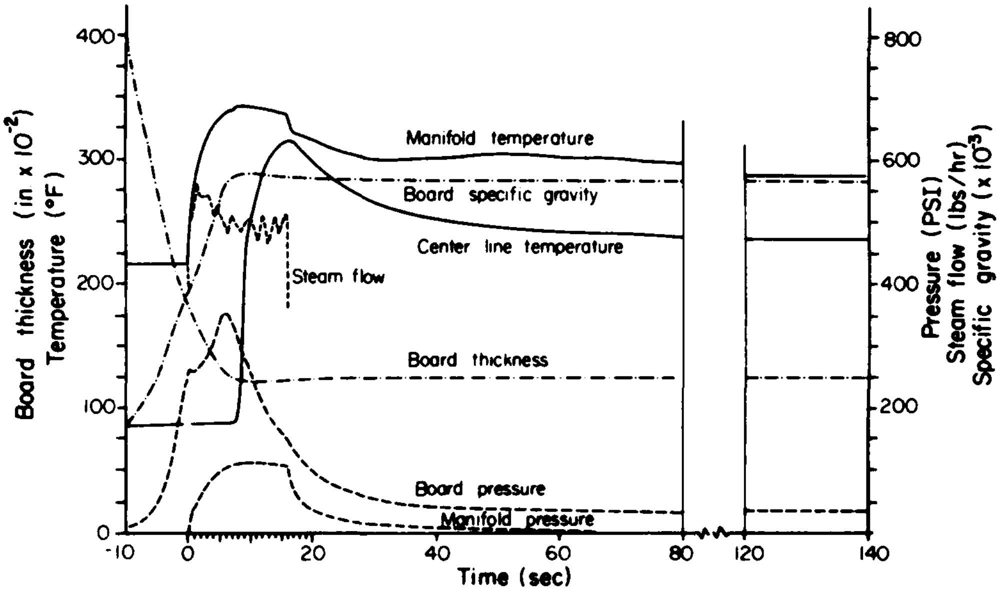

Figure 5.—Proper selection of variables 0.093 in. s closing speed and 16 seconds of steam permit a 1-1 4-inch-thick 0.560 SG board (4 13) to be cured in 140 seconds press time. (ML85 5078)

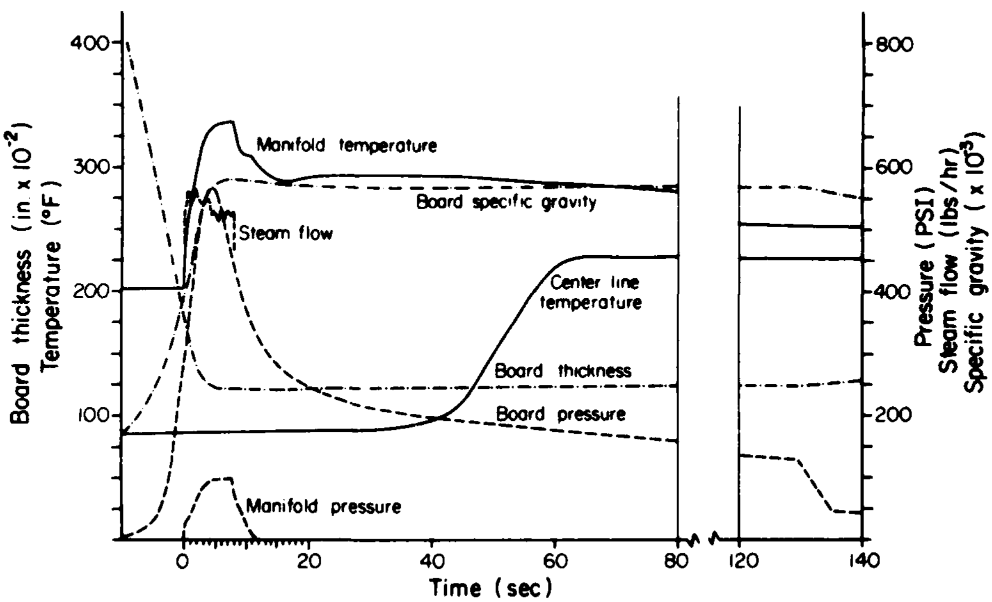

Figure 6.—Board delamination occurs when centerline temperature rise is delayed by fast closure (0.192 in. s) and a reduced (8 s) steam time—1-1/4-inch-thick 0.560 SG board (4 13a). (ML85 5077)

The fate of the boards was decided in the next *8 seconds*. The pressure in the board made at the slower press closing rate (4/13) was arrested for 2 seconds, indicating that steam was penetrating and plasticizing the material. At the end of 6 seconds, the board had been compressed to a SG of 0.550 and board pressure peaked at 350 lb/in.^{2}. Centerline temperature began to rise after 7.5 seconds and passed the 212 °F mark 9 seconds after initial steam entry. This point (212 °F centerline temperature) occurred 0.5 second after the press had reached its minimum opening and the board's SG was 0.575, very close to the upper limit of 0.577 defined as critical in the basics of steam pressing. Centerline temperature climbed to a maximum of 315 °F by the end of the 16-second steaming period. Sixty seconds into the press cycle the centerline temperature had dropped to, and stabilized at, 240 °F. Board pressure at this time was only 35 lb/in.^{2}. The induced heat was sufficient to accelerate the resin cure, and a board free of delamination was produced in 140 seconds.

In contrast, steam failed to penetrate to the center of board 4/13a. The faster closing rate, 0.193 versus 0.093 in./s, permitted only a slight alteration in the rate of pressure increase during closure, and a maximum board pressure of 570 lb/in.^{2} was reached 4.5 seconds after steam introduction. This point of maximum pressure occurred 0.5 second prior to the board reaching a maximum SG of 0.575. The combination of the fast close and a short, 8-second steam period precluded an early rise in centerline temperature. Sixty seconds elapsed before temperatures finally surpassed 212 °F. The *80 seconds* remaining in the press cycle were insufficient to allow the resin to cure. The board completely delaminated.

Steam injection not only provides a stabilized resin-curing temperature (approximately 225 °F) sooner than conventional pressing but also accelerates the process by exposing the board to elevated temperatures for a short period of time. Contrast the resin-curing, time/temperature relations occurring in board 4/13a with those that took place in the 1/2-inch 0.640 SG board 5/24d (table 1 and fig. 7). Low levels of steam energy, 80 and 99 Btu's, were used to manufacture both boards. Centerline temperatures stabilized between 230 and 235 °F in each case. However, only *55 seconds* above a temperature of 212 °F were sufficient to complete the resin cure in board 5/24d after a very short exposure to a temperature of 300 °F had accelerated the process.

1-1/4-Inch-Thick 0.721 SG Boards (Table 4)

The heat transfer problem caused by easy escape of steam through the edge of a low-density thick board is replaced by an entry problem when the target board density is increased. An increase in mass demands that more time be allowed at lower mat densities to obtain adequate steam penetration. Timing is critical in achieving optimum heat transfer.

A press closing schedule that worked well with the 1-1/4-inch-thick 0.721 SG board type incorporated closure rates of approximately 0.12 in./s during initial steam entry. After centerline temperature had risen above 212 °F, closure speed was increased to compress the mat rapidly and achieve maximum temperature with a minimum use of steam. When steam injection was postponed beyond a SG of 0.260 as in boards 4/18c and 5/23a, the delay in centerline temperature rise resulted in severe board delamination. Press programs in both of these cases incorporated low or medium steam flow rates. Edge and corner delaminations in boards 4/21c and 4/21d were also attributed to low steam flow rates and the accompanying temperature differentials.

Resin cure as discussed earlier is a function of time as well as temperature. The corner delamination in board 5/23c is attributed to a very slow rise in temperature at this position. While it took only 5.5 and 9.0 seconds, respectively, to reach 220 °F in the center and edge positions, 66 seconds elapsed before the temperature passed 220 °F in the corner (fig. 8).

In contrast, all monitored positions—center, edge, and corner—of a similarly pressed but fully cured board (5/23b) passed the 220 °F mark within 15 seconds. Except for an increase from 540 to 720 lb/h steam flow rate during the first 4 seconds of pressing board 5/23b, the press closing schedules for both boards were identical. Results from this portion of the study indicate *higher* steam flow rates permit shorter press cycles by reducing temperature variations within the board. When cure temperatures have been reached in all sections of the board, they can be maintained by a *reduced* flow. A 1-1/4-inch 0.721 SG board having high bending properties and adequate IB was made in 71 seconds using 167 Btu's steam energy.

2-Inch-Thick 0.480 SG Boards (Table 5)

No problems were encountered in pressing 2-inch-thick 0.480 SG boards. Press schedules were compromised between steam flow rates, entry SG, and press closure rate to provide adequate steam penetration while preventing excessive resin precure or steam energy consumption. Moderate steam flow rates of 540 lb/h were used during the initial period of steaming. Because of the mass and thickness of the mat, the delay in center temperature rise is relatively long, 4-8 seconds. Corner position temperature rise is usually delayed an additional 2-5 seconds.

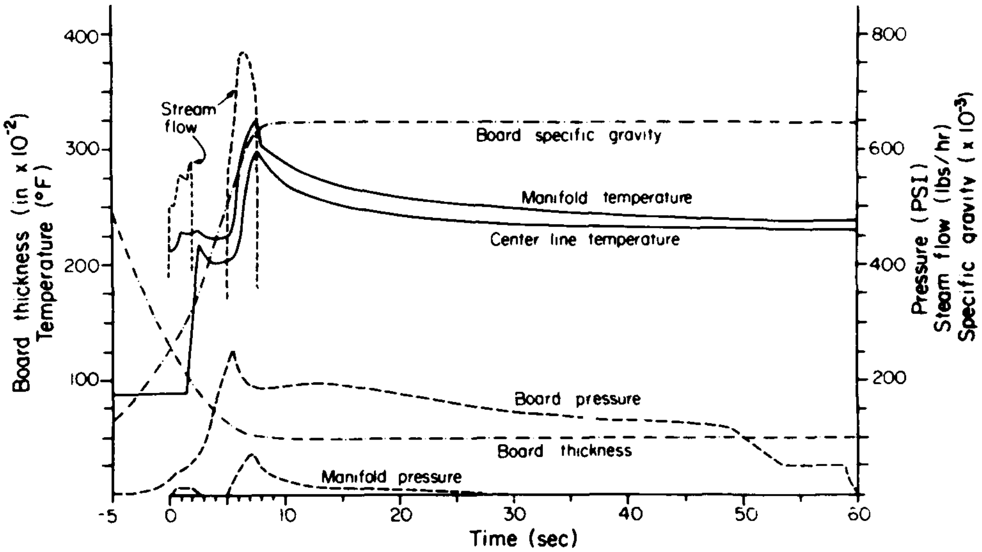

Figure 7.—A brief exposure to maximum temperatures of 325 °F permits resin cure at 235 °F in 60 seconds press time. 1 2-inch-thick 0.640 SG board (5/24d). (ML85 5076)

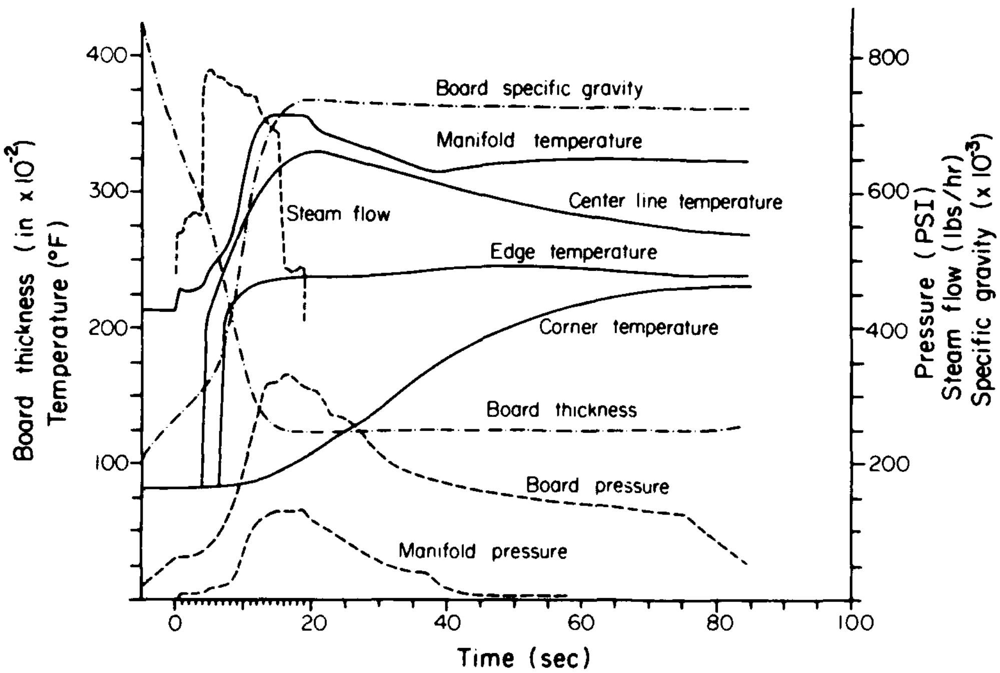

Figure 8.—Delay in corner temperature rise results in delamination of this portion of the board. 1-1 4-inch-thick 0.721 SG board (5 23c). (ML85 5075)

A high steam flow rate (720 lb/h) was used in some portion of each press cycle to reduce within-board temperature differentials. Maximum temperatures at the corner position of the various boards ranged from 227 to 270 °F. A board made in 150 seconds with 111 Btu's steam energy had acceptable board properties. Press time was shortened to 55 seconds when steam energy was increased to 204 Btu's.

Density profiles were uniform in all boards except 5/19b and 5/20. Press cycles specified a late steam entry and a shorter steam time for both of these boards. Density levels varied from a plus 30 to a minus 20 percent of average.

2-Inch-Thick 0.64 SG Boards (Table 6)

High flow rates were again used in manufacturing the 2-inch-thick 0.64 SG boards. A low steam flow rate in the initial period of steaming was disastrous and caused complete delamination of board 5/20c. Press times were successfully reduced from 320 to 201 seconds in boards 5/3a, 5/3b, and 5/20b using steaming schedules that provided between 185 and 200 Btu's energy. Change to a faster closing rate and overpressing slightly to compensate for springback resulted in lower corner temperatures and caused corner delamination in board 5/3c.

Two inches is about the maximum board thickness that can be pressed with the described steam-injection equipment. Steam passing through the face layers of a thicker board escapes through the edges before it can reach the core. Increasing steam-line pressure would increase the practical thickness range for steam-injection pressing in addition to alleviating some of the temperature differential problems in thinner boards. Means to prevent large temperature differentials from occurring throughout the board should be considered in any scale-up to commercial size panels.

Summary

A pressing method utilizing saturated steam injected directly into the mat during the closing period can be used to accelerate the cure of 2-inch-thick isocyanate-bonded aspen flakeboards. Pressing schedules and resultant board properties given here show the latitudes and limitations of the system for boards of various thicknesses and SG's. A 2-INCH-THICK 0.640 SG BOARD WAS MADE IN 201 SECONDS using added steam energy of 185 Btu/lb of OD board (Btu's). One-half-inch-thick 0.640 SG boards can be made in 60 seconds using 99 Btu's. In some cases increasing the amount of steam energy permitted press times to be reduced. A 1/2-inch-thick 0.640 SG board was made in 40 seconds using 177 Btu's. In other cases, especially involving high SG boards (0.800) which are prone to blister, a balance between press time and energy input must be maintained.

Corner and edge delaminations were traced to temperature differentials occurring at these extremities and are believed to be caused by a pressure drop between the center and edge of the boards. This problem, which is more severe in thicker, low-density boards, can be reduced by the use of high steam flow rates.

Steam flow rates can be changed during the press cycle to optimize press time and energy consumption. Each board thickness and SG combination require a different press schedule. Whereas increasing the flow rates during steaming time is advantageous to thin boards, the reverse is true for some SG levels of thick boards.

The upper thickness limit of steam-injection pressing using the described equipment is about 2 inches. Steam passing through the face layers of a thicker board escapes through the edges prior to reaching the centerline. The basics of steam-injection pressing using saturated steam in an unsealed system were found to apply to all ranges of board thicknesses and SG: *steam must be introduced prior to the mat reaching a SG level of 0.448, and a centerline temperature of 212 °F must be reached before the mat is compressed to a SG of 0.577.*

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Table 1.—Pressing schedule and physical properties of 1/2-inch-thick 0.640 specific gravity steam-injected boards

Board number	Total press time	Steam energy[a]	Pressing variables: Steam flow: Entry specific gravity[b]	Time period	Rate	Specific gravity at end of period	Closure rate[c]		Temperature delay[d]	Maximum temperature: Center	Edge	Corner	Pressure: Steam entry[e]	Maximum	Board properties: Moisture content[f]: In	Out	Thickness	Bending: Specific gravity	Modulus of elasticity	Modulus of rupture	Internal bond	Linear expansion[g]: 65 percent relative humidity	Vacuum pressure soak	Thickness swelling[g]: 65 percent relative humidity	Vacuum pressure soak	Remarks
	s	Btu/lb		s	Lb/h		In/s	ΔSG/s	s	°F			Lb/in.²		Pct				K/lb/in.²	Lb/in.²	Lb/in.²	Pct				
5-25	120	98	0.260	2	540	0.330	0.130	0.035	1	303	295	240	30	230	3.7	3.0	0.513	0.605	525	3700	91	0.20	0.33	3.5	32.7	
				3	0	.500	.110	.056																		
				2	720	.600	.053	.050																		
				2	0	.650	.020	.025																		
5-24d	60	99	.250	2	540	.335	.162	.042	1.5	296	303	288	40	260	3.7	3.1	.520	.598	519	3630	86	.20	.33	3.8	33.1	
				3	0	.500	.105	.055																		
				2	720	.615	.060	.057																		
				3	0	.660	.012	.015																		
5-24a	40	177	.380	2	540	.500	.101	.060	1	329	315	296	175	280	2.7	—	.499	.604	545	3510	89	.22	.39	4.9	32.4	
				5	720	.665	.032	.033																		
5-24b	22	158	.325	3	540	.500	.115	.058	1	324	303	322	110	230	3.1	3.6	.503	.621	544	3900	79	.21	.36	4.6	34.6	Blister
				3	720	.625	.042	.042																		
				2	0	.670	.017	.022																		
5-24e	22	101	.250	2	540	.330	.155	.040	1	—	297	266	40	215	3.7	3.1	.543	.581	457	2904	77	.22	.34	3.4	30.3	Soft core
				3	0	.500	.110	.057																		
				2	720	.610	.058	.055																		
				3	0	.665	.015	.019																		
5-25a	13.5	121	.228	6	540	.525	.132	.050	1	284	283	280	30	275	3.7	3.0	.556	.532	364	2440	59	.24	.43	4.9	38.4	Edge delamination
				5	0	.665	.026	.028																		
				2	0	.675	.003	.004																		

[a]Steam energy in Btu/lb of ovendry board.
[b]Mat specific gravity (SG) at the time of initial steam flow.
[c]ΔSG/s = average change in SG per second for the period.
[d]Time between steam entry and temperature rise in the center of the board.
[e]Mat pressure at the time of initial steam flow.
[f]Moisture content of mat going in and coming out of the press.
[g]Values based on preliminary OD conditions.

Table 2.—Pressing variables and physical properties of 1 2-inch-thick 0.801 specific gravity steam-injected boards

Board number	Total press time	Steam energy[a]	Steam flow: Entry specific gravity[b]	Steam flow: Time period	Steam flow: Rate	Steam flow: Specific gravity at end of period	Closure rate[c]	Closure rate[c]	Temperature delay[d]	Maximum temperature: Center	Maximum temperature: Edge	Maximum temperature: Corner	Pressure: Steam entry[e]	Pressure: Maximum	Moisture content[f]: In	Moisture content[f]: Out	Thickness	Bending: Specific gravity	Bending: Modulus of elasticity	Bending: Modulus of rupture	Internal bond	Linear expansion[g]: 65 percent relative humidity	Linear expansion[g]: Vacuum pressure soak	Thickness swelling[g]: 65 percent relative humidity	Thickness swelling[g]: Vacuum pressure soak	Remarks
	s	Btu lb		s	Lb h		In s	ΔSG s	s	F	F	F	Lb in 2	Lb in 2	Pct	Pct			K lb in 2	Lb in 2	Lb in 2	Pct	Pct	Pct	Pct	
3 PERCENT ISOCYANATE																										
5 26a	140	307	0 280	3	670	0 385	0 130	0 035	0 5	310	296	290	60	325	3.5	4.2	0.520	0.732	619	4130	86	0 21	0.37	5.0	55.6	325° platen, a few blisters
				8	670	745	062	045																		
				4	670	825	013	030																		
5 25d	120	140	395	8	540	785	063	048	—	—	251	260	275	575	3.5	4.8	572	—	—	—	—	—	—	—	—	300° platen, blisters and delamination
				2	0	815	009	015																		
				2	0	850	010	017																		
5 25b	60	148	280	4	540	550	175	068	1 5	307	298	248	75	405	3.3	4.1	.522	747	727	5480	108	.24	45	3.6	39 5	375° platen, blisters
				4	720	790	055	060																		
				3	0	850	012	020																		
7 PERCENT ISOCYANATE																										
5 26b	172	373	270	5	540	420	105	030	—	—	290	286	45	330	4.0	3.5	.494	.746	743	5592	217	.20	22	4 1	35 3	Screen on top
				8	690	775	053	042																		
				4	690	80	007	011																		
				2	690	80	—	—																		
5 26c	152	317	280	6	540	435	085	026	1	296	305	289	40	265	4.0	3.8	.523	710	662	4920	140	.20	29	4.2	30 8	
				10	690	770	040	033																		
				5	0	800	004	006																		
5 26e	102	576	265	11	690	675	083	037	1	330	312	304	40	280	4.0	7.5	528	.710	680	5225	166	.21	33	4.3	28 0	Blisters
				9	690	775	008	011																		
				10	690	780	—	—																		

[a]Steam energy in Btu lb of ovendry board.
[b]Mat specific gravity (SG) at the time of initial steam flow.
[c]ΔSG s average change in SG per second for the period.
[d]Time between steam entry and temperature rise in the center of the board.
[e]Mat pressure at the time of initial steam flow.
[f]Moisture content of mat going in and coming out of the press.
[g]Values based on preliminary OD conditions.

Table 3.—Pressing variables and physical properties of 1-1 4-inch-thick 0.560 specific gravity steam-injected boards

Board number	Total press time	Steam energy[a]	Steam flow: Entry specific gravity[b]	Steam flow: Time period	Steam flow: Rate	Steam flow: Specific gravity at end of period	Closure rate[c]	Closure rate[c]	Temperature delay[d]	Maximum temperature: Center	Maximum temperature: Edge	Maximum temperature: Corner	Pressure: Steam entry[e]	Pressure: Maximum	Moisture content[f]: In	Moisture content[f]: Out	Thickness	Bending: Specific gravity	Bending: Modulus of elasticity	Bending: Modulus of rupture	Internal bond	Linear expansion[g]: 65 percent relative humidity	Linear expansion[g]: Vacuum pressure soak	Thickness swelling[g]: 65 percent relative humidity	Thickness swelling[g]: Vacuum pressure soak	Remarks
	s	Btu lb		s	Lb h		In s	ΔSG s	s	°F	°F	°F	Lb/in.²	Lb/in.²	Pct	Pct			K/lb/in.²	Lb/in.²	Lb/in.²	Pct	Pct	Pct	Pct	
4.15b	200	155	0.345	7	720	0.550	0.108	0.029	2.5	280	—	—	155	220	2.4	3.3	1.228	0.560	484	3160	79	0.18	0.31	2.0	23.6	
				5	720	570	009	004																		
4.14d	180	55	340	8	260	570	104	029	7.5	275	—	—	165	445	3.1	3.4	1.315	—	—	—	—	—	—	—	—	Edge delamination
				4	260	570	—	—																		
5.23	140	155	350	7	720	545	110	029	1.5	318	255	245	145	205	2.9	3.5	1.227	.564	482	3080	67	.16	.36	2.1	24.7	
				5	720	570	011	005																		
4.13	140	155	385	6	540	555	093	028	8	315	—	—	260	350	2.4	3.5	1.250	.549	455	2930	55	.19	.36	2.7	26.6	
				10	540	570	003	015																		
4.13a	140	80	385	5	540	570	118	037	40	226	—	—	280	570	3.1	2.0	—	—	—	—	—	—	—	—	—	Total delamination—slow temperature rise
				3	540	580	007	003																		
4.15	100	190	330	9	260	575	100	027	7	300	—	—	155	480	2.5	3.8	1.252	.553	486	2940	66	.19	.34	2.3	23.8	Corner delamination
				31	260	570																				
4.18b	100	185	335	6	540	570	143	039	3	335	—	—	155	330	2.7	4.2	1.234	.568	532	3600	60	.16	.36	2.1	24.7	
				10	720	570																				
4.14e	60	370	335	8	720	570	107	029	3	331	—	—	140	210	3.4	3.0	1.223	.555	460	2860	65	.19	.34	2.1	21.8	
				24	720	570																				
4.13b	60	185	380	7.5	540	570	082	025	4	304	—	—	235	350	2.8	2.4	1.301	.544	406	2560	52	—	—	—	—	Edge delamination
				8.5	540	570																				

[a]Steam energy in Btu lb of ovendry board.
[b]Mat specific gravity (SG) at the time of initial steam flow.
[c]ΔSG s average change in SG per second for the period.
[d]Time between steam entry and temperature rise in the center of the board.
[e]Mat pressure at the time of initial steam flow.
[f]Moisture content of mat going in and coming out of the press.
[g]Values based on preliminary OD conditions.

Table 4.—Pressing variables and physical properties of 1-1/4-inch-thick 0.721 specific gravity steam-injected boards

Board number	Pressing variables														Board properties											
	Total press time	Steam energy[a]	Steam flow						Tempera-ture delay[d]	Maximum temperature			Pressure		Moisture content[f]		Thick-ness	Bending			Internal bond	Linear expansion[g]		Thickness swelling[g]		Remarks
			Entry specific gravity[b]	Time period	Rate	Specific gravity at end of period	Closure rate[c]			Center	Edge	Corner	Steam entry[e]	Maximum	In	Out		Specific gravity	Modulus of elasticity	Modulus of rupture		65 percent relative humidity	Vacuum pressure soak	65 percent relative humidity	Vacuum pressure soak	
	s	Btu/lb		s	Lb/h		In./s	ΔSG/s	s	°F	°F	°F	Lb/in.²	Lb/in.²	Pct	Pct	In.		K/lb/in.²	Lb/in.²	Lb/in.²	Pct	Pct	Pct	Pct	
4-25a	210	158	0.260	5	720	0.315	0.121	0.011	4	303	—	—	45	315	3.1	4.3	1.250	0.713	667	5170	101	0.19	0.33	2.7	35.8	
				8	720	.700	.196	.048																		
				3	720	.710	.006	.003																		
4-21d	210	60	.260	6	260	.330	.122	.012	27	250	237	—	40	720	2.7	3.6	1.468	—	—	—	93	—	—	—	—	Delamination—all edges
				8	260	.730	.187	.050																		
4-21b	150	110	.260	5	540	.345	.170	.017	5	301	255	—	40	300	2.7	4.2	1.273	.722	740	6100	94	.15	.30	2.4	35.2	
				7	540	.730	.197	.055																		
4-21c	150	90	.260	4	260	.300	.115	.010	7	277	250	—	60	520	2.9	4.6	1.437	—	—	—	79	—	—	—	—	Delamination—all edges
				9	540	.725	.196	.047																		
				4	260	.730	.002	.001																		
4-18c	90	150	.325	13	540	.730	.118	.031	23	265	232	—	180	785	3.0	3.7	—	—	—	—	—	—	—	—	—	Delamination—slow temperature rise
				7	540	.730	—	—																		
4-21a	90	135	.260	5	540	.310	.112	.010	3	313	260	—	40	330	2.7	4.6	1.247	.709	663	6100	100	.16	.29	2.0	35.5	
				8	720	.705	.203	.049																		
				3	540	.735	.017	.010																		
5-23c	84	171	.260	4	540	.310	.139	.012	4	330	245	231	60	220	4.0	5.1	1.399	—	—	—	68	—	—	—	—	Corner delamination
				10	720	.700	.162	.039																		
				5	540	.735	.012	.007																		
5-23b	71	167	.260	4	720	.320	.162	.015	4.5	290	240	270	40	280	3.5	5.6	1.327	.667	776	5530	81	.16	.24	2.0	29.9	
				10	720	.705	.154	.039																		
				5	540	.735	.010	.006																		
5-23a	65	151	.330	3	360	.395	.149	.022	10	235	118	90	150	750	3.7	5.1	—	—	—	—	78	—	—	—	—	Complete delamination—slow temperature rise
				13	720	.750	.083	.027																		
				3	360	.750	—	—																		

[a]Steam energy in Btu/lb of ovendry board.
[b]Mat specific gravity (SG) at the time of initial steam flow.
[c]ΔSG/s = average change in SG per second for the period.
[d]Time between steam entry and temperature rise in the center of the board.
[e]Mat pressure at the time of initial steam flow.
[f]Moisture content of mat going in and coming out of the press.
[g]Values based on preliminary OD conditions.

Table 5.—Pressing variables and physical properties of 2-inch-thick 0.480 specific gravity steam-injected boards

Board number	Total press time	Steam energy[a]	Steam flow: Entry specific gravity[b]	Steam flow: Time period	Steam flow: Rate	Steam flow: Specific gravity at end of period	Closure rate[c]	Closure rate[c]	Temperature delay[d]	Maximum temperature: Center	Maximum temperature: Edge	Maximum temperature: Corner	Pressure: Steam entry[e]	Pressure: Maximum	Moisture content[f]: In	Moisture content[f]: Out	Thickness	Specific gravity	Bending: Modulus of elasticity	Bending: Modulus of rupture	Internal bond	Linear expansion[g]: 65 percent relative humidity	Linear expansion[g]: Vacuum pressure soak	Thickness swelling[g]: 65 percent relative humidity	Thickness swelling[g]: Vacuum pressure soak	Remarks
	s	Btu/lb		s	Lb/h		In/s	ΔSG/s	s	°F	°F	°F	Lb/in.^{2}	Lb/in.^{2}	Pct	Pct			K/lb/in.^{2}	Lb/in.^{2}	Lb/in.^{2}	Pct	Pct	Pct	Pct	
5-4	325	210	0.330	10	540	0.455	.080	0.012	4.5	302	249	250	130	130	3.3	4.6	1.935	0.496	328	2060	58	0.32	0.44	2.4	19.6	
				5	720	.495	.034	.008																		
				10	720	.495	—	—																		
5-4c	205	190	.330	15	540	.485	.060	.010	7.5	293	—	270	140	150	2.8	4.3	1.963	.491	313	2220	50	.22	.42	2.9	19.5	
				5	720	.485	—	—																		
				5	540	.485	—	—																		
5-19b	150	111	.380	10	540	.480	.053	.010	4	298	235	—	230	230	3.9	5.6	1.990	.497	354	2350	46	.22	.41	2.8	20.3	
				5	720	.480	—	—																		
5-20	70	140	.380	10	540	.485	.054	.010	10	280	240	227	220	220	3.3	5.2	2.006	.492	362	2480	43	.18	.33	3.7	20.7	
				7	720	.485	—	—																		
5-19a	55	204	.330	15	540	.480	.060	.010	7.5	287	245	248	135	140	3.9	5.9	2.003	.474	336	2300	49	.20	.31	2.9	20.7	
				5	720	.480	—	—																		
				5	540	.480	—	—																		

[a]Steam energy in Btu/lb of ovendry board.
[b]Mat specific gravity (SG) at the time of initial steam flow.
[c]ΔSG/s = average change in SG per second for the period.
[d]Time between steam entry and temperature rise in the center of the board.
[e]Mat pressure at the time of initial steam flow.
[f]Moisture content of mat going in and coming out of the press.
[g]Values based on preliminary OD conditions.

Table 6.—Pressing variables and physical properties of 2-inch-thick 0.641 specific gravity steam-injected boards

Board number	Total press time	Steam energy[a]	Steam flow: Entry specific gravity[b]	Steam flow: Time period	Steam flow: Rate	Steam flow: Specific gravity at end of period	Closure rate[c]		Temperature delay[d]	Maximum temperature: Center	Maximum temperature: Edge	Maximum temperature: Corner	Pressure: Steam entry[e]	Pressure: Maximum	Moisture content[f]: In	Moisture content[f]: Out	Thickness	Bending: Specific gravity	Bending: Modulus of elasticity	Bending: Modulus of rupture	Internal bond	Linear expansion[g]: 65 percent relative humidity	Linear expansion[g]: Vacuum pressure soak	Thickness swelling[g]: 65 percent relative humidity	Thickness swelling[g]: Vacuum pressure soak	Remarks
	s	Btu/lb		s	Lb/h		In/s	ΔSG/s	s	F			Lb/in²		Pct				K/lb/in²	Lb/in²	Lb/in²	Pct				
5-3a	320	200	0.330	10	720	0.455	0.107	0.012	8.5	315	—	—	130	330	3.1	4.6	2.076	0.658	517	3890	83	0.19	0.29	3.1	30.0	
				10	720	.630	.078	.018																		
				8	720	.650	.008	.002																		
				6	210	.650	—	—																		
5-3b	286	190	.365	10	720	.480	.084	.011	7	332	252	240	200	280	3.4	4.3	2.091	.659	503	4060	67	.20	.33	3.3	30.7	
				10	720	.660	.072	.018																		
				5	720	.660	—	—																		
				6	260	.660	—	—																		
5-20c	286	140	.360	11	360	.500	.099	.013	156	132	110	111	200	720	—	—	—	—	—	—	—	—	—	—	—	Complete delamination
				10	720	.675	.066	.018																		
				5	720	.650	—	—																		
				5	360	.650	—	—																		
5-3c	270	215	.355	18	720	.690	.097	.019	10	242	236	220	210	650	3.1	4.2	2.066	.675	595	3440	64	—	—	—	—	Corner delamination
				6	720	.685	—	—																		
				6	260	.685	—	—																		
5-20b	201	185	.365	10	720	.480	.084	.011	5	337	280	260	210	275	—	—	—	.655	504	3500	74	.18	.37	3.1	31.4	
				20	720	.640	.067	.016																		
				5	720	.655	.009	.003																		
				5	260	.655	—	—																		
5-20a	139	175	.360	10	720	.490	.094	.013	7	325	240	241	210	425	3.0	4.8	1.967	.687	550	3880	—	—	—	—	—	Corner delamination
				10	720	.675	.072	.018																		
				5	720	.680	.003	.001																		
				6	260	.680	—	—																		

[a]Steam energy in Btu/lb of ovendry board.
[b]Mat specific gravity (SG) at the time of initial steam flow.
[c]ΔSG/s = average change in SG per second for the period.
[d]Time between steam entry and temperature rise in the center of the board.
[e]Mat pressure at the time of initial steam flow.
[f]Moisture content of mat going in and coming out of the press.
[g]Values based on preliminary OD conditions.

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The Forest Products Laboratory (USDA Forest Service) has served as the national center for wood utilization research since 1910. The Laboratory, on the University of Wisconsin-Madison campus, has achieved worldwide recognition for its contribution to the knowledge and better use of wood.

Early research at the Laboratory helped establish U.S. industries that produce pulp and paper, lumber, structural beams, plywood, particleboard and wood furniture, and other wood products. Studies now in progress provide a basis for more effective management and use of our timber resource by answering critical questions on its basic characteristics and on its conversion for use in a variety of consumer applications.

Unanswered questions remain and new ones will arise because of changes in the timber resource and increased use of wood products. As we approach the 21st Century, scientists at the Forest Products Laboratory will continue to meet the challenge posed by these questions.

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